SEPARABLE MODULATOR

BACKGROUND

This application is a continuation-in-part of US Patent Application No. 10/078,282, filed February 19, 2002, which is a divisional of application No. 09/991,378 filed on November 21, 2001, which is a continuation of application No. 08/769,947 filed on December 19, 1996, now abandoned, which is a continuation-in-part of application No. 08/238,750 filed on May 5, 1994, now Patent No. 5,835,255, and which is a continuation in part of application No. 08/554,630 filed on November 6, 1995, now abandoned.

Spatial light modulators used for imaging applications come in many different forms. Transmissive liquid crystal device (LCD) modulators modulate light by controlling the twist and/or alignment of crystalline materials to block or pass light. Reflective spatial light modulators exploit various physical effects to control the amount of light reflected to the imaging surface. Examples of such reflective modulators include reflective LCDs, and digital micromirror devices (DMD™).

Another example of a spatial light modulator is an interferometric modulator that modulates light by interference, such as the iMoD™. The iMoD employs a cavity having at least one movable or deflectable wall. As the wall, typically comprised at least partly of metal, moves towards a front surface of the cavity, interference occurs that affects the color of light viewed at the front surface. The front surface is typically the surface where the image seen by the viewer appears, as the iMoD is a direct-view device.

Currently, iMoDs are constructed of membranes formed over supports, the supports defining individual mechanical elements that comprise the picture elements (pixels) of an image. In a monochrome display, such as a display that switches between

black and white, one iMoD element might correspond to one pixel. In a color display, three iMoD elements may make up each pixel, one each for red, green and blue.

The individual iMoD elements are controlled separately to produce the desired pixel reflectivity. Typically, a voltage is applied to the movable wall of the cavity, causing it be to electrostatically attracted to the front surface that in turn affects the color of the pixel seen by the viewer. Since the iMoD is based upon a membrane, however, some objectionable artifacts may occur around the edges of the elements. As the membrane deflects or deforms towards the front surface, it typically does not achieve a uniform flatness. The portions of the membrane that curve away from the fully-deformed membrane held tightly against the front surface are at differing distances away from the front surface, which may result in the objectionable artifacts.

Since the iMoD typically functions as a direct-view device, the back surface of the movable portion of the cavities may be operated upon without negatively affecting the image quality. This may also provide more freedom in other aspects of the manufacture of these devices.

SUMMARY

One embodiment of the invention is a separable modulator architecture. The modulator has a mirror suspended from a flexible layer over a cavity. The flexible layer may also form supports and support posts for the mirror.

An alternative embodiment of the separable modulator architecture has a mirror suspended over a cavity. The mirror is supported by a flexible layer, supports and support posts. The flexible layer forms the supports and rests on top of the support posts. In this embodiment, the support posts are fabricated separately from the flexible layer.

In yet another alternative embodiment, a bus structure is formed above the flexible layer. The bus structure is arranged so as to electrically connect to, and be physically supported by, all of or a subset of the support posts.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may be best understood by reading the disclosure with reference to the drawings, wherein:

Figure 1 shows an embodiment of an interferometric modulator.

Figure 2 shows an alternative embodiment of an interferometric modulator.

Figure 3 shows a cross-sectional view of an interferometric modulator.

Figure 4 shows a cross-sectional view of another embodiment of an interferometric modulator.

Figure 5 shows a cross-sectional view of an embodiment of an interferometric modulator having address bussing behind a flex layer.

Figures 6a-6g show cross-sectional views of a modulator throughout the early steps of an embodiment of a process to manufacture interferometric modulators.

Figures 7a-7f show cross-sectional views of a modulator throughout the later steps of an embodiment of a process to manufacture interferometric modulators using a planarizing layer.

Figures 8a-8d show cross-sectional views of a modulator throughout the later steps of an embodiment of a process to manufacture interferometric modulators without a planarizing layer.

Figures 9a-9f show cross-sectional views of the later steps of a process to manufacture interferometric modulators having an address bussing behind a flex layer.

Figures 10a and 10b show alternative embodiments of back plane supports for a separable interferometric modulator.

Figures 11a-11d show layouts and cross-sectional views of alternative embodiments of interferometric modulators in which pixel color may be controlled by flexible layer properties.

Figures 12a and 12b show cross-sectional views of embodiments of interferometric modulators in which landing pads are used to modify the electromechanical properties of the moving mirror and flexible layers.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Figure 1 shows a side view of an interferometric modulator. The modulator 2 is arranged on a transparent substrate 10, which is typically glass. A primary mirror 12 is arranged on top of an electrode that allows for addressing of individual elements of an array of interferometric modulators. Suspended above a cavity 14 is a secondary mirror 16, which rests upon, or is part of, a membrane 15. Support arms such as 13 may be part of the same layer as the membrane 15, support the mirror 16 and attach it to the support posts 18. The support arms and the membrane 15 are flexible. This allows the secondary mirror 16 to be moved into the cavity 14, bringing it closer to the primary mirror and thereby affecting the interference properties of the cavity.

Generally, the secondary mirror assumes a quiescent state in which it is away from the primary mirror, which may also be referred to as the 'white' state or the far position. It must be understood that the 'white,' or ON, state may be any discrete color other than white. Any pixel made up of a number of individual colored elements, such as red, green and blue, may appear white to the viewer as will be discussed in more detail below.

When the two mirrors are separated, the resulting pixel in the image appears white or ON. When a voltage is applied to one or the other mirror, an electrostatic potential builds in the cavity and it draws the secondary mirror towards the primary mirror. The movement of the mirror changes the dimensions of the cavity. In a 'near' position, the interference effects cause the resulting pixel to be black, in a monochrome system. Alternatively, the near position could cause the interference to result in other colors of light, such as red, green and blue, as will be discussed further.

Changing the interference properties of the cavity 14 allows the image viewed from the front side of the transparent substrate 10, the side opposite to that upon which the modulator is arranged, to change. For example, a picture element (pixel) corresponding to the interferometric modulator element 4 may show up as a black pixel, if the image being viewed on the front surface were monochrome. For color images, there may be three interferometric modulator elements for each pixel viewed on the front. This will be discussed in more detail later.

As can be seen in element 4 of Figure 1, there is an area 17 where the curve of the support arm may cause a varying distance between the primary mirror and the secondary mirror. This varying distance may in turn affect the interference properties of the cavity around the edges of the observed pixels. It is possible to suspend the secondary mirror from a back support to alleviate this problem.

As can be seen in Figure 2, the secondary mirror 24 is suspended over the primary mirror 22 by a back support 26. The substrate 20 is a transmissive substrate, such as glass as well. The configuration shown in Figure 2 may provide better control of the fringe effect that occurs in configurations such as Figure 1. In addition, the elevated line 28 may provide an opportunity to position the control interconnections away from the substrate, thereby increasing the available active area for pixels on the transmissive substrate.

Cross-sectional views of alternative embodiments of interferometric modulators that provide better performance than the current implementations are shown in Figures 3, 4 and 5. In Figure 3, modulator 100 comprises a mirror 38 suspended over a cavity by a membrane 40. The glass substrate 30 has formed upon it an electrode layer 32, and an optical stack formed of a metal layer, such as chrome, 34 and an oxide layer 36. In this embodiment, membrane 40, which may be a flexible metal and therefore referred to here as the flex layer, comes into contact with the optical stack layers forming support posts.

In contrast, modulator 200 of Figure 4 has support post plugs such as 42, upon which the flex layer 40 rests. The mirror 38 remains suspended over the cavity as in the previous modulator, but the flex layer does not form the support posts by filling holes between the flex layer and the optical stack. Rather, the support posts are formed of a planarization material, as will be discussed in more detail later.

In Figure 5, yet another embodiment of the interferometric elements is shown. This particular embodiment of modulator 300 is based upon the modulator 200 of Figure 4, but may be adapted to work with either of the embodiments 100 or 200, as well as other configurations of the interferometric modulators. In the embodiment 300, an extra layer of metal or other conductive material has been used to form a bus structure 44. This will allow signal routing along the back of the interferometric modulators, possibility eliminating a number of electrodes that may otherwise have had to be formed on the glass substrate.

The modulators 100, 200 and 300 have different configurations, but have some processing steps in common. The initial processes used to form the various configurations are shown in Figures 6a-6g. Figure 6a shows the formation of an electrode layer 32 out of an appropriate material, such as indium tin oxide (ITO), and an optical stack layer of metal 34 such as chrome. These materials are formed on a transparent substrate 30. The viewing surface of the transparent substrate is on the 'bottom' of the substrate, the opposite side of the substrate than that upon which the electrode and optical stack layers are formed. In a process not shown here, the electrode and metal layers 32 and 34 are patterned and etched to form electrode columns, rows or other useful shapes as required by the display design.

Formed on top of the metal layer 32 and filling in the gaps between the patterned electrode elements are an oxide layer 36, a first sacrificial layer 46 and the mirror metal layer 38 in Figure 6b. The first sacrificial layer 46 will determine the dimension of the

cavity over which the mirror is suspended. As discussed above, color modulators may be formed by using three modulator elements for each pixel in the resultant image. In interferometric modulators, the dimension of the cavity determines the nature of the interference. As discussed previously, moving the mirror fully towards the optical stack in a monochrome implementation causes a 'colored' pixel to turn 'black.' Similarly, moving the mirror partially towards the optical stack may result in the pixel color changing to values different from the quiescent color value.

One method of forming color pixels is to construct cavities of differing depths such that the resultant quiescent colors from three different depths of cavities are red, green and blue. The interference properties of the cavities are directly affected by their depth. In order to affect these varying cavity dimensions, three layers of sacrificial layer 46 may be deposited. A first layer will be deposited, masked and patterned thus defining the area of one of the three modulators forming each pixel; a second layer would then be deposited. A second mask would then be applied to this layer, and it would be patterned to define the combined area of the first modulator defined above as well as the second modulator forming each pixel. Finally, a third sacrificial layer would be applied. This third layer need not be patterned, since its thickness will be included in all three of the modulators forming each pixel.

The three individual deposited layers described here would not necessarily be of the same thickness. This would result in one modulator for each pixel having a thickness combined of three layers, one modulator having a thickness combined of two layers, and one modulator having a thickness of a single sacrificial layer. When the sacrificial layer materials are removed, the cavity dimensions will vary according to the various combined thicknesses of the three sacrificial layers, resulting in three different colors such as red, green and blue.

Returning to Figure 6c, a photoresist layer 48 is deposited and patterned appropriately. The structure is then etched as dictated by the photoresist pattern, forming mirrors on top of sacrificial islands 50 as shown in Figure 6d. A second sacrificial layer 51 is then deposited in Figure 6e. Photoresist 52 is then applied to the second sacrificial layer and patterned in Figure 6f. In Figure 6g portions of the first, 46, and second, 51, sacrificial layers have been etched away to form locations such as 54b for support posts and 54a for supports, and the photoresist layer has been stripped away. .

At this point in the process, the methods of manufacturing either modulator 100 from Figure 3 or modulator 200 from Figure 4 diverge. The modulator 200 of Figure 4 having the support post plugs 42 has processes as shown in Figures 7a-7f. In Figure 7a, the structure as shown in Figure 6g has added to it a planarization layer 56. The planarizing material fills the locations 54a and 54b. The planarization material is partially removed as shown in Figure 7b, forming support post plugs 58. The flex layer, which may also be referred to as the mechanical layer 40 is then applied over the support post plugs in Figure 7c.

A photoresist layer 62 is applied and patterned in Figure 7d. This is used as an etch mask to pattern the flex layer 40. In Figure 7e, the flex layer 40 has been patterned. The effects of the patterning are not noticeable in the cross sectional view shown here. A back view of the modulator elements showing embodiments of the flex layer patterning will be discussed with regards to Figures 10a and 10b. Finally, if no bussing layer is to be used, the sacrificial layers are removed, typically by plasma etch, in Figure 7f. The resulting modulator 200 has a cavity 60, in which the mirror is suspended over the optical stack.

Returning to Figure 6g, the processing for the modulator 100 will now be discussed. Instead of applying a planarizing layer as discussed in Figure 7a, the metal layer 40 is applied directly to the second sacrificial layer 51 and locations 54a and 54b, as

is shown in Figure 8a. This causes the flex layer to form the support posts, where it fills locations 54b and to form the back supports where it fills locations such as 54a. This approach has the advantage of eliminating the planarization process, which may simplify both the manufacturing process and the resultant structure.

Once the flex layer 40 is applied, a photoresist 62 is used to pattern the flex layer 40, as shown in Figure 8b. In Figure 8c, while not discernable from this view, the flex layer 40 has been patterned to create the unique mechanical properties of the modulator that will be discussed further. Finally, in Figure 8d the sacrificial layers have been removed, forming the cavity 60 in modulator 100. In this embodiment, no back bussing structure was used.

An example of the process flow for adding a back bussing structure is shown in Figures 9a-9c. The process shown begins with the structure formed in Figures 7e and 8c, after patterning of the flex layer, but prior to the removal of the sacrificial layers. For discussion purposes, the modulator configuration having the support post plugs as in Figure 7e is used, but could be equally applicable to embodiments where no support post plug exists as in Figure 8c.

In Figure 9a, a third sacrificial layer 64 is applied to the flex layer 40. A photoresist layer 66 is applied in Figure 9b. The photoresist layer is then patterned and the structure etched to form holes, such as 69. In Figure 9c, a conductive bus layer 68 is applied providing contact between the bus layer 68 and the flex layer 40 through the hole 69. This provides electrical connection such that signals on the bus layer 68 can be used to control the flex layer 40.

In Figure 9d, a photoresist layer 70 is applied and patterned. In Figure 9e, the bus layer 68 is patterned and etched or otherwise removed so that the remaining portions of the bus layer 68 form the bus structure 71 of Figure 9f. In Figure 9f, the sacrificial layers are also removed, resulting in modulator 300, having bus structure 71 and cavity 60.

The bus structure is possible because of the optical shielding provided by the mirror between the viewing side of the substrate and the back of the flex layer. This provides the ability to separate the optical and the electro-mechanical properties of the modulator. The optical properties, improved by the use of the suspended mirror 38 in any of the embodiments, are separated from the electro-mechanical properties such as addressing and the movements that result from that addressing. This separable modulator architecture allows more freedom in the use of the back of the modulator, as it prevents any processes performed on the back of the flex membrane or structures added from affecting the optical performance of the modulator.

Possible patterns used on the back of the flex membrane 40 are shown in Figures 10a and 10b. These views are from the back of the modulator, which may also be seen as the top of the modulators shown in the previous figures. In Figure 10a, the sacrificial layer 52 was patterned to form the large center back support 74 surrounded by four small supports 76a-d that were subsequently filled in by flex layer 40. The layer 40 would only be patterned and removed from the edges of the membrane to separate it from the adjacent modulator elements, otherwise suspending the mirror from the support posts 72a-72b.

Alternatively, in Figure 10b, the flex layer is patterned to form thin, linear straps 78a-d connected to each support post 72a-d. The straps are attached to the mirror by center support 74. These two alternatives, among many others, may affect the freedom of movement of the mirror and the detailed mechanical characteristics of that movement. In some cases, this may be an advantage.

For example, in the color modulator example given above, three masking and depositing processes were needed to form three different cavity depths. As an alternative, the detailed mechanical characteristics of the flexible layer, the support structure, and the interface between the flex layer and the support posts can be altered by the various design and process parameters. This allows the same depth cavity to be used for pixels of

different colors. The various design parameters modify the quiescent position of the mirror within the cavity upon removal of the sacrificial layers.

One possible pixel configuration 80 is shown in Figure 11a. This view is as seen by the viewer from the front surface of the substrate, and is comprised of nine elements, three for each of the colors red, green and blue. The modulator 802 may correspond to blue, 804 to green and 806 to red, as shown. These three different colors may be achieved by varying the distance between the mirror and the optical stack. When a voltage is applied to the modulators, they may all move a uniform distance towards the electrode or they may all move different distances toward the electrode. Indeed, all three modulators may traverse the entire cavity and move to a near position that brings them into direct contact with the substrate. The dimensions of the cavities in the quiescent state are shown by the vertical dimensions 82, 84 and 86, in Figures 11b, 11c and 11d, respectively.

For example, one mirror 38a of one modulator corresponding to one color of the resulting pixel may have back supports, a flex layer and support post interfaces designed to cause the mirror to settle at a distance 82, smaller than the as-fabricated sacrificial layer. A second mirror 38b of one modulator corresponding to another color may have back supports, a flex layer, and support post interfaces designed to cause the mirror to settle at the as-fabricated thickness 84 of the sacrificial layer, after the sacrificial layer is removed. Finally, a third mirror 38c of another modulator corresponding to yet another color may have back supports, a flex layer and support post interfaces designed to cause the mirror to settle at a distance 86 larger than the as-fabricated thickness of the sacrificial layer, after removal of the sacrificial layer. In this way, controlling the mechanical properties and/or the physical restraints of the supports result in three different cavity dimensions, and thus three different pixel colors are created using a single thickness of sacrificial material.

Alternatively, the modulators could all be released from the sacrificial layers and all stay at the same position. The differing characteristics of the flex layer and supports could be manipulated to cause the mirrors to move different distances upon application of the same voltage. As yet another alterative, the modulators could all have the same structures, but differing voltages applied for differing colors.

In addition to the freedom afforded by separating the electro-mechanical properties of the modulator from the optical properties, a suspended mirror provides other opportunities. As was discussed above, the suspended mirror alleviates objectionable artifacts that may occur due to the curvature of the membrane. As discussed above, a black state for the pixels can be achieved by deflecting the mirror very close to or into direct contact with the optical stack on the front surface of the cavity. Both of these methods of achieving a dark state can have drawbacks. Holding an array of mirrors at a very small gap electrostatically can require the modulator to be constructed with incredibly high precision. Allowing the mirror to come into direct contact with the optical stack prevents the designer from using certain incompatible combinations of mirror/optical stack materials.

In order to remove these limitations it is possible to fabricate on top of the oxide layer 36 an arrangement of small landing pads 90 as shown in Figure 12a applied to modulator 100. Such landing pads can be constructed of common thin-film-process-compatible material using the same deposition and lithography techniques used for the other layers of the iMoD. These landing pads can be small enough so as to be essentially invisible to the human eye while being distributed across the front face of the entire cavity so as to affect operation of the entire mirror 38.

Several different purposes can be achieved with these landing pads. Landing pads can allow complete freedom in the choice of the optical stack material, since the landing pads prevent the mirror 38 from contacting the oxide layer 36. Indeed, insulating landing

pads 90 would in principle allow the top layer of the optical stack to be a conductor rather than an insulator. Landing pads can change the mechanical operation of the iMoD by changing the electric field distribution in the cavity. Landing pads can enable a dual mode sort of operation in which the mirror 38 stays flat until it hits the landing pads and then, with increasing voltage, bends as would a membrane to allow each pixel to achieve multiple, precise color values.

A second landing pad configuration is shown in Figure 12b in which the flex layer 40, rather than the mirror 38, contacts the landing pad 92. In this manner, the modulator has two separate ranges of mechanical behavior, one before the flex layer contacts the landing pad and one after. This allows multiple colors per pixel to be achieved with precise uniformity set by the thickness of the landing pads 92.

In this manner, the manufacture and operation of interferometric modulators may be improved. The suspended mirror increases the usable active area for creating a resulting pixel in the image and eliminates many possible objectionable artifacts. The support structure attaching to the mirror on the back side also provides more freedom in the manufacturing process. Interconnections enabled by the back support may also result in fewer electrodes having to be deposited on the glass, resulting in more available glass area. The separation of the optical properties from the electro-mechanical properties may result in previously unavailable opportunities, due to the separation of the flex membrane from the optical properties of the modulator.

Thus, although there has been described to this point a particular embodiment for a method and apparatus for interferometric modulators and their methods of manufacture, it is not intended that such specific references be considered as limitations upon the scope of this invention except in-so-far as set forth in the following claims.